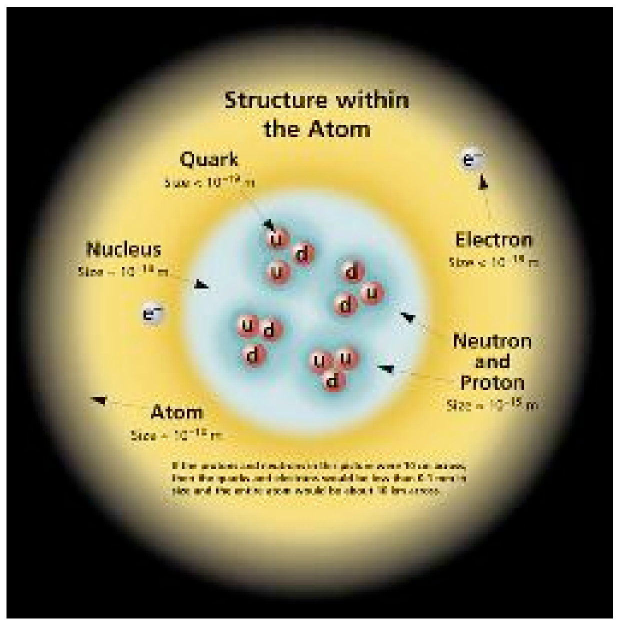
Introduction to Nuclear and Particle Physics - 8.701
Lecture 1
Introduction

Bernd Surrow

Massachusetts Institute of Technology

Outline

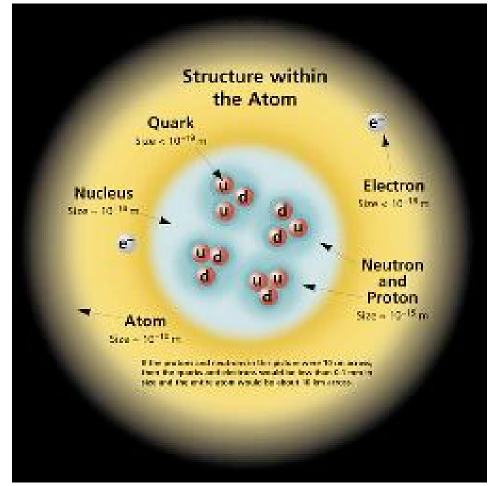
- Experimental aspects in particle physics
- Units in particle physics
- Basic ingredients of particle physics



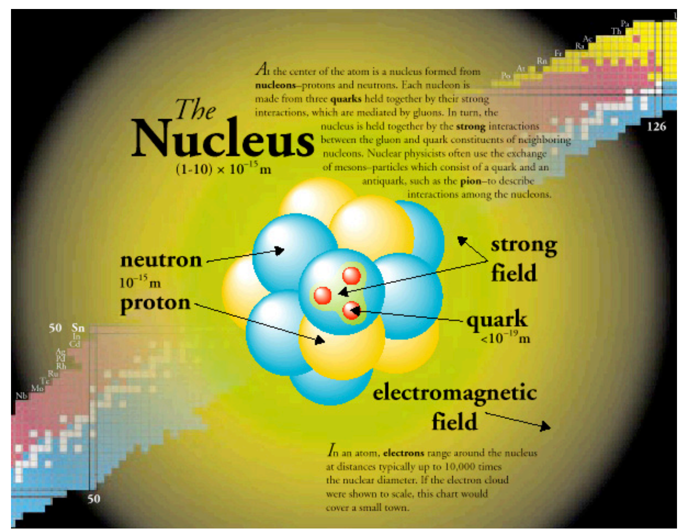
- Time travel in the particle physics world
- Definition: Nuclear and Particle Physics
- Summary

Definition: Nuclear and Particle Physics

- What is matter made of?
  - This questions has a long tradition in mankind and finds its first attempts to come up with an answer in the Greek natural philosophy
  - However, real experimental work on the structure of matter did not start until the end of the 19th century with the discovery of radiation by Bequerrel in 1896 besides the work by Marie and Pierre Curie (The 1903 Nobel prize in physics was awarded to Bequerel, Marie and Pierre Curie)
  - Series of experiments led to our current understanding: scattering experiments and spectroscopy
  - Theoretical framework: Theory of relativity and quantum mechanics: Quantum Field Theory



- The domain of nuclear and particle physics
  - Nuclear physics: Physics of many-body systems of strongly interacting matter (properties, structure, force and reactions)
  - Particle physics: Physics of elementary particles (quarks and leptons) and fundamental fields/interactions (electromagnetic, strong and weak interactions and gravitation)



Basic ingredients of Particle Physics

- The Standard Model (Building blocks of matter)
  - Quarks and leptons: Elementary particles known today
    - Quarks: Fermions (spin 1/2 particles)
    - Leptons: Fermions (spin 1/2 particles)
  - Electrons and neutrinos (Released for example in radioactive beta-decay) are members of the lepton family
  - Atoms consist of: Nucleus (Protons and neutrons) and electrons
  - Protons and neutrons consist of: Quarks
    Generally: Hadrons = Baryons (3 quark states) + Mesons (2 quark states)

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c²	Electric charge	Flavor	Approx. Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Basic ingredients of Particle Physics

- The Standard Model (Interactions among building blocks of matter)
  - Strong, electromagnetic and weak interactions between fermions mediated by gauge bosons
  - Gauge theories are crucial in description of SM interactions:
    - Dirac Lagrangian: Free relativistic spin 1/2 particle
    - Demand local gauge invariance of Dirac Lagrangian (Example here: U(1) ⇒ QED):
    - Local gauge invariance (U(1), SU(2) or SU(3) symmetries) introduces SM gauge fields

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$$

$$\psi(x) \longrightarrow e^{i\alpha(x)}\psi(x)$$

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - m\bar{\psi}\psi$$

$$D_{\mu} \equiv \partial_{\mu} - ieA_{\mu}$$

$$A_{\mu} \rightarrow A_{\mu} + \frac{1}{e}\cdot\partial_{\mu}\alpha$$

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Basic ingredients of Particle Physics

- The Standard Model (Interactions among building blocks of matter)

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	60	
for two protons in nucleus	10^{-36}	Not applicable to hadrons	20

Property \ Interaction	Weak (Electroweak)	Electromagnetic (Electroweak)
Acts on:	Flavor	Electric Charge
Particles experiencing:	Quarks, Leptons	Electrically charged
Particles mediating:	W^+ W^- Z^0	γ
Strength relative to electromag for two u quarks at: 10^{-18} m	0.8	1
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-4}	1
for two protons in nucleus	10^{-7}	1

Units in Particle Physics

- Units of energy
  - Elementary particles are so small that the normal mechanical units are inconvenient. The unit of electron volt (eV) was therefore introduced: The energy which an electron acquires when accelerated through a potential difference of 1 Volt ⇒ $1eV = 1.602 \bullet 10^{-19} J$
  - Typical energies: keV (nuclear physics), MeV and GeV (particle physics)
  - The mass of the proton is roughly 1GeV/c ($0.938 GeV/c^2$)
- Units cross-section
  - Cross-section (Unit: area) are often expressed in barns: $1barn = 1b = 10^{-24}\ cm^2$
- Natural units
  - Two fundamental constants: $\hbar = h/2\pi = 1.055 \bullet 10^{-34}$ Js and $c = 2.998 \bullet 10^8$ m/s
  - It is convenient to use a system of units in which $\hbar$ is one unit of action (ML^2/T) and c is one unit of velocity (L/T). Our system of units is then completely defined if we specify for example our energy unit (ML^2/T^2).
  - By choosing units with $\hbar=c=1$, it becomes unnecessary to write $\hbar$ and c explicitly in formulas. It is customary to speak of mass (m), momentum (mc) and energy (mc^2) all in terms of GeV and to measure length ($\hbar/mc$) and time ($\hbar/mc^2$) in units of GeV^{-1}:

Conversion factor	$\hbar=c=1$ units	Actual dimension
$1kg = 5.61 \bullet 10^{26}$ GeV	GeV	GeV/c^2
$1m = 5.07 \bullet 10^{15}\ GeV^{-1}$	GeV^{-1}	$\hbar c/GeV$
$1s = 1.52 \bullet 10^{24}\ GeV^{-1}$	GeV^{-1}	$\hbar/GeV$

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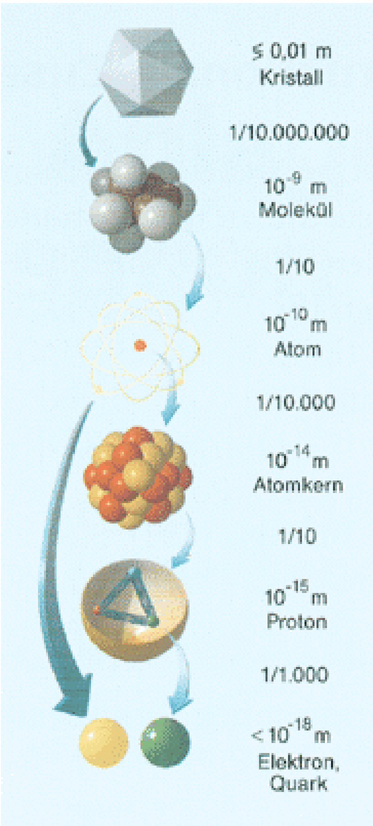
Experimental aspects of Particle Physics

- General comments

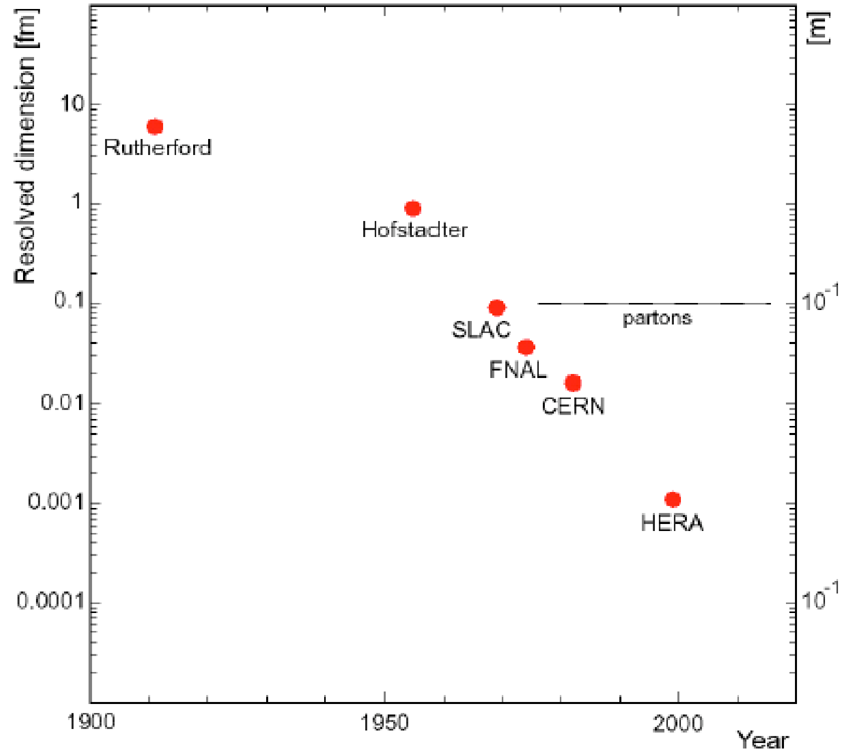


Rutherford (1911)

Hofstadter (1953)

HERA (1997)

Probing smaller distances requires larger momentum transfer: probe ⇒ target



- A particle of momentum p has an associated wavelength, λ, given by the de Broglie formula: $\lambda = h/p$
- Large (small) wavelength resolves large (small) structures
- Manifestation of Heisenberg's uncertainty principle: $\Delta p \bullet \Delta x \approx \hbar$
  $\Rightarrow$ Probe particle needs a momentum of at least $p \approx \hbar/\Delta x$ to resolve structures of size Δx

Experimental aspects of Particle Physics

- Type of experiments
  - Scattering experiments:
    - Classical approach: 1. Scatter point-like probe onto object (target) whose structure should be investigated 2. Deduce information on the structure of the target from a measurement of the final-state (e.g. scattered probe) 3. Measure cross-section and compare to theoretical predictions
    - Generally: Collision of particles with subsequent detection of decay products and cross-section measurement
    - Higher energies are necessary to resolve smaller objects!
  - Spectroscopy:
    - Experiments which aim to measure the decay products of an excited state, i.e. the measurement of the decay-rate and comparison to theoretical predictions
    - Higher energies are necessary to produce heavier excited states
- Production of particles
  - Cosmic rays:
    - Particle flux of secondary particles (e.g. muons) which are produced in the earth's atmosphere by high-energetic particles (e.g. protons) from outer space
    - Rate of a reasonable size detector is small and uncontrollable
  - Nuclear reactors:
    - Production of decay particles from radioactive nuclear disintegration, e.g neutrons and neutrinos
  - Particle accelerators:
    - Fixed target experiments in which an accelerated particle particle beam is directed onto a stationary target
    - Storage rings: Collide different accelerated particle beams (proton-proton, electron-proton and electron-positron)
    - Beneficial to operate in collider mode than in fixed target mode to achieve highest possible center-of-mass energy

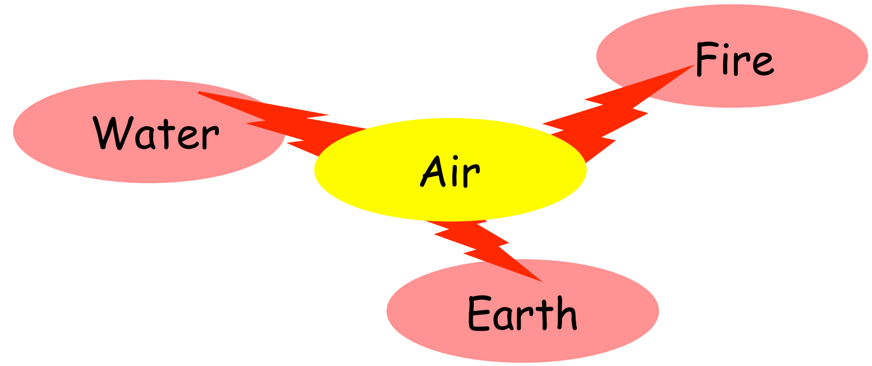
Experimental aspects of Particle Physics

- Detection of particles
  - Main idea:
    - Employ the reaction of energetic particle beams with matter which is part of our detector
    - Characteristic processes are the basis for particle detection devices such as:
      - Charged particles: Energy loss, Cherenkov radiation and Bremsstrahlung
      - Photons: Photoelectric effect, Compton scattering and pair production
  - Types of today's detection systems:
    - Nuclear and particle physics detection systems are based on the above process which particles encounter while traversing through matter
    - Those detection systems can be classified by their basic task to measure the kinematics and properties of final-state particles:

1. Position: Localize the hits of a charge particle and determine the decay point of a short-lived particle (Position sensitive detectors, e.g. silicon-strip detectors)
2. Momentum: Determine the momentum of a charged particle in a magnetic field from a reconstruction of the curvature of a track
$$p_{\perp} \approx 0.3 \cdot B \cdot R \left[\frac{\mathrm{GeV/c}}{\mathrm{Tm}}\right]$$
3. Energy: Deposition of energy in a localized detector volume (Calorimetry)
4. Mass: (Particle identification - PID): $m = \sqrt{E^2 - p^2}$
5. Charge: Orientation of curvature of a charged particle track in a magnetic field

Time travel in the Particle Physics World

- The Greek natural philosophy
  - One of the first attempts to answer the question of what matter is made of was proposed by *Anaximenes of Miletus*:
  - Remarkable simple idea to decompose the world around us into basic finite components!
  - One problem: It's wrong!



- Periodic table of elements
  - Mendeleev's proposal: Truly quantitative and in agreement with experimental facts
  - Regular arrangements: Stepping stone to nuclei and thus to protons and neutrons

PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lantha- nides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford. (261.1089)	105 Db Dubnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Bh Bohrium (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 (269, 273)	111 (272)	112 (277)						

Lanthanide series	57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide series	89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)

Time travel in the Particle Physics World

The Classical era (1897-1932) (1)

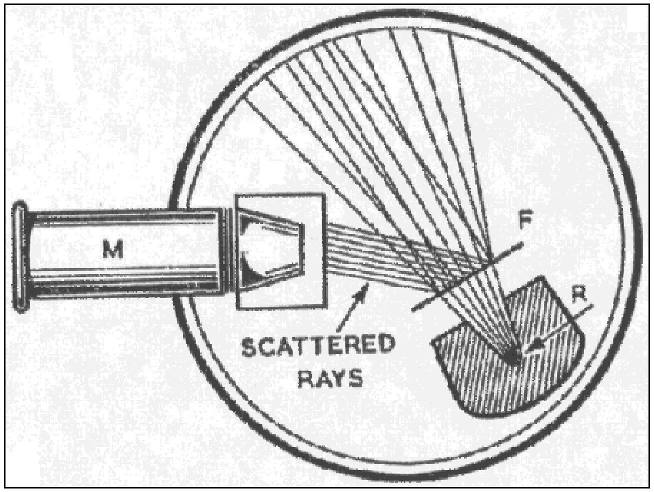
- J. J. Thomson: Discovery of the electron
  - Cathode rays emitted by a hot filament are deflected by a magnet
    $\Rightarrow$ Rays have a charge of negative value (Direction of curvature!)
  - Determination of the e/m ratio which turned out to be very large
  - Indirect evidence pointed to the case that the corpuscles are very light (Thomson called the charge electron!)

- Thomson atomic model:
  - Electrons are constituents of atoms
  - Electrons are suspended in a heavy, positively charged paste, like the plums in a pudding

Time travel in the Particle Physics World

The Classical era (1897-1932) (2)

- Rutherford and colleagues fired a beam of α-particles (ionized He-atoms) into a thin sheet of gold foil
- The majority of α-particles passed through the gold foil completely undisturbed, but a few of them bounced off at angels larger than 90°
- Conclusion (Rutherford's Atomic Model): 1911
  - The core of the atom is positively charged,
  - with virtually all of the atomic mass and
  - occupies only a tiny fraction of the volume of the atom (Estimated radius: 10^{-14} m)
- Atomic model by Bohr: 1914
  - Electrons circulate around the atomic nucleus on discrete orbits (This is in striking contrast to classical electrodynamics!)
  - Quantitative description of Hydrogen spectrum
  - Assumption that heavier elements consist of two or more protons failed!
- Discovery of the neutron by Chadwick: 1932
- Classical period of particle physics: electrons, protons and neutrons!



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Time travel in the Particle Physics World

- The Photon (1900-1924)
  - Black-body radiation by Max Planck (1900):
    - Planck was attempting to explain the so-called blackbody spectrum for the electromagnetic radiation emitted by a hot object
    - Classical statistical mechanics predicted that the total power radiated should be infinite
    - Solution: Planck was able to explain experimental results if he assumed that the electromagnetic radiation is quantized, coming off a hot surface in little packages: $E = h\nu$
  - Photoelectric effect by Einstein (1905):
    - Quantization is a feature of electromagnetic field itself and has nothing to do with the emission mechanism
    - Photo-electric effect: $E \leq h\nu - w$ (Electromagnetic radiation which strikes a metal surface allows to release electrons of energy E!) $\Rightarrow$ Particle nature of light!
    - Millikan (1916): Clear experimental verification of Einstein's photoelectric effect!
  - Compton effect by Compton (1923):
    - Light that is scattered from a particle at rest is shifted in wavelength, according to (λ is the incident wavelength, λ' is the scattered wavelength, θ is the scattering angle θ and $\lambda_c = h/mc$ is the Compton wavelength):

$$\lambda' = \lambda + \lambda_c(1 - \cos\theta)$$

    - Result can be obtained if one treats light as a particle of zero mass with energy given by Planck's equation and apply the laws of conservation of (relativistic) energy and momentum
    - Light behaves like a particle: Photon

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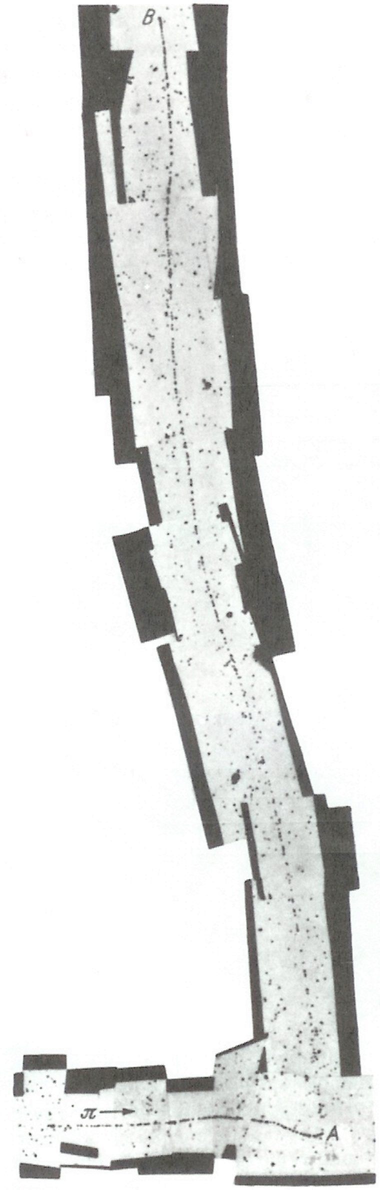
Time travel in the Particle Physics World

- Mesons (1934-1947)
  - A force must exist inside the nucleus that binds the protons (and neutrons) together which is more powerful than the force of electrical repulsion
  - The first significant theory of strong force was proposed by Yukawa in 1934:
    - Short-range: Mediated particle must be rather heavy
    - Yukawa estimated that its mass should be nearly 300 times the electron mass
    - Yukawa called the particle : meson ("middle-weight" compared to leptons and baryons)
  - Experimental evidence:
    - First indications by Anderson in 1937 were not conclusive
    - Clear evidence: Powell et al. (1947): Photographic emulsion exposed to cosmic rays at high altitude



$\pi \to \mu + \nu$

Time travel in the Particle Physics World

- Antiparticles (1930-1956)
  - Non-relativistic quantum mechanics (1923-1926)
  - Relativistic quantum mechanics: Dirac equation

$$i\hbar\gamma^\mu\partial_\mu\psi - mc\psi = 0$$

Solution for free particle with p=0 ($E=mc^2$):

$$\psi^{(1)} = e^{-i(E/\hbar)t}\begin{pmatrix}1\\0\\0\\0\end{pmatrix}$$

Electron (spin up)

$$\psi^{(2)} = e^{-i(E/\hbar)t}\begin{pmatrix}0\\1\\0\\0\end{pmatrix}$$

Electron (spin down)

$$\psi^{(3)} = e^{+i(E/\hbar)t}\begin{pmatrix}0\\0\\1\\0\end{pmatrix}$$

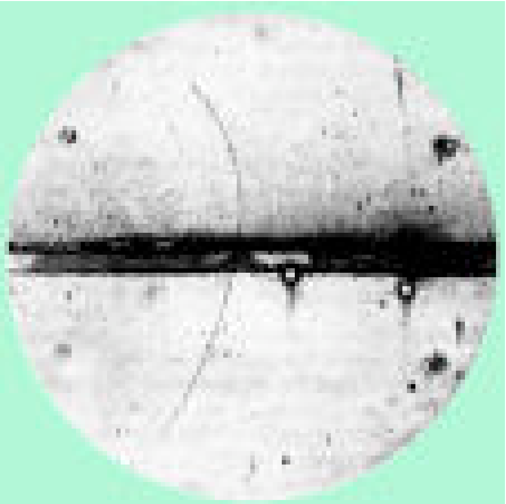
Positron (spin up)

$$\psi^{(4)} = e^{+i(E/\hbar)t}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}$$

Positron (spin down)

- Feynman-Stuckelberg formulation of negative energy solutions are re-expressed as positive-energy states of a different particle than the electron:
  - Electron and position appear on the same footing
  - Profound and universal feature of quantum-field theory: For every particle there is an anti-particle

- Discovery of the positron (1932) by Anderson:
  - Photograph of a track left in a cloud chamber by a cosmic ray particle inside a magnetic field
  - In order to clarify weather this track refers to a downward moving negative or a upward moving positive charged particle, a lead plate was placed across the center of the chamber. The resulting curvature pointed to an upward moving positively charged particle!

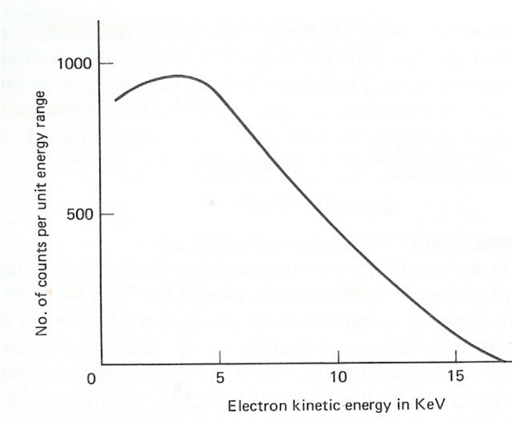


Time travel in the Particle Physics World

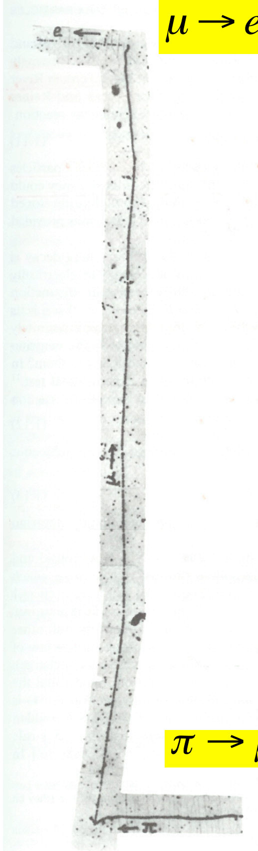
- Neutrinos (1930-1962)
  - In nuclear beta decay, a radioactive nucleus A is transformed into a slightly lighter nucleus B, with the emission of an electron: $A \to B + e^-$
  - If the nuclear beta decay would occur only as such as two-body decay, then the energy of the outgoing electron would be kinematically determined:
  - However, experimental data of the electron kinetic energy of the beta decay spectrum of tritium shows that the energy of the electron varies considerably.
  - A solution was proposed by Pauli: Another particle was emitted along with the electron that caries off the missing energy!
  - Fermi incorporated Pauli's idea in a quantitative description of nuclear beta-decay and called the particle neutrino:

$$n \to p^+ + e^- + \bar{\nu}$$

  - Experimental verification: Savannah River nuclear reactor (1953):
    - Inverse beta-decay provided clear evidence: $\bar{\nu}_e + p \to n + e^+$
  - The existence of a second (muon-type) neutrino was established in 1962:
    - Using 10^{14} anti-neutrinos from π^- decay, Lederman, Schwartz and Steinberger identified 29 instances of: $\bar{\nu}_\mu + p \to n + \mu^+$
    - And no cases of: $\bar{\nu}_\mu + p \to n + e^+$



$\mu \to e + \bar{\nu}_e + \nu_\mu$



$\pi \to \mu + \nu$

Time travel in the Particle Physics World

Strange particles (1947-1960)

- By 1947, it seemed that several problems in particle physics were solved…!
- Not for long…:
  - In December 1947,Rochester and Butler published the cloud chamber photograph which turned out to be the production of a neutral K-meson: $K^0 \rightarrow \pi^+ + \pi^-$
  - In 1949, Powell published the decay of a charged Kaon: $K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$
  - In 1950, Anderson discovered the Lambda baryon: $\Lambda \rightarrow p^+ + \pi^-$
  - All those particles seemed "strange" in the sense that they are produced copiously (10^{-23} s), but they decay relatively slowly (10^{-10} s)!
  - Gell-Mann assigned those particles a new quantum number called strangeness besides their respective charge:
    - Production of two strange particles: $\pi^- + p^+ \rightarrow K^+ + \Sigma^-$

      $\pi^- + p^+ \rightarrow K^0 + \Sigma^0$

      $\pi^- + p^+ \rightarrow K^0 + \Lambda$
    - *Assign strangeness quantum number S: S=+1 for Σ and S=-1 for Λ with S=0 for p,n and π*
- *The garden of particle which seemed so tidy in 1947 grew into a real mess of a particle zoo by 1960. The "elementary particles" awaited a "Periodic Table"!*
- *Next: Classification according to underlying quantum numbers!*